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RESEARCH ARTICLE

QUARTZ FIBER RADOME AND SUBSTRATE FOR AEROSPACE APPLICATIONS

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ABSTRACT

Quartz fiber is an ultra-high purity silica glass having immediate use applications on radomes and satellite communications for aerospace systems. In this study, the uses of quartz fiber as an antenna radome and a dielectric substrate were investigated for a patch antenna designed to operate at f=8 GHz. In order to compare the performance of quartz fiber as an antenna radome, glass fiber is examined for the same antenna. For the dielectric substrate case, quartz fiber is compared with the well-known and widely used dielectric substrate of FR-4. The electromagnetic properties of the quartz fiber were examined for different temperature values using a free space measurement setup and a controllable furnace. The antenna parameters, including radiation pattern, gain, return loss and beamwidth, are investigated and compared in detail for all cases in order to demonstrate the effects of using quartz fiber as a radome and an antenna substrate. The results highlight that quartz fiber shall have high-end use for low electromagnetic interference characteristics without compromising on structural integrity.

Keywords: Quartz fiber, Glass fiber, Radome, Substrate, Antenna

1. INTRODUCTION

Quartz fiber, which is also known as fused silica fiber or silica glass fiber, is a type of fiber made from quartz glass. Quartz is a type of ultra-pure crystalline silica. Quartz fiber is preferred due to its unique properties, such as high strength, high temperature resistance as well as low thermal expansion coefficient [1-3]. The history of quartz fiber dates back to the early 20th century, when researchers began exploring the potential of silica as a material for making fibers. Researchers at Corning Glass Works developed a process for making fibers from silica glass in 1930s. This process covered melting high-purity silica and drawing it into fibers using a special apparatus. Since then, Quartz fiber has been used in a variety of applications, including insulation, reinforcement, and structural support. In the 1960s, quartz fiber was used to make the first optical fibers, which revolutionized the telecommunications industry. Today, quartz fiber is used in a variety of applications, including telecommunications, aerospace, and automotive industries, as well as in scientific researches [4-6].

By definition, a radome is a protective cover or enclosure that is used to protect radar or other types of antennas from the external elements. Quartz fiber-made radomes are used in a variety of applications, including satellite communication, air traffic control, and radar systems. Quartz fiber-made radomes are chosen for their high transparency to electromagnetic waves, which makes them ideal for use with radar and other types of antennas. They are also resistant to extreme temperatures and UV radiation, making them suitable for use in a variety of extreme environments. In addition, radomes made by using quartz fiber are very durable and have a long lifespan, making them a cost-effective choice for many applications [7-9]. On the other hand, radomes made with quartz fiber can be more expensive than other traditional radomes because of the initial high cost of quartz raw material. Because of the fragile and brittle nature of quarts, they require careful handling and processing during manufacture. Despite these

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challenging properties, radomes made with quartz fiber are widely used in a variety of applications due to their unique combination of transparency, durability, and resistance to extreme conditions [10, 11]. In the literature, Yaoyao Wang studied the applicability of quartz fiber-based radomes for high frequencies, specifically between 10-20 GHz [8]. As well, there are several other studies on the use of quartz as substrate and radome [12]. In a study conducted by Dyck et al., quartz is used as the substrate of an antenna operating at 300 GHz [14]. In another study, Xu et al. investigated quartz glass as the substrate of a patch antenna array for radar applications [15].

In line with this, antennas operating in this frequency range are used in a variety of applications, including satellite communication, radar, and wireless networking. Patch antennas is composed of a ground plane, radiating patch and a dielectric substrate which is mostly preferred as FR-4 due to its relatively high performance and low-cost. Patch antennas are known for their high gain and narrow beam width, which makes them well suited for directional communication and radar applications. They are also relatively simple and inexpensive to manufacture, which makes them a popular choice for many applications. However, patch antennas are sensitive to the size and shape of the patch and the dielectric constant of the substrate, so careful design and manufacturing are required to achieve the desired performance characteristics. The substrate is typically a dielectric material, which is a type of insulating material that can support the propagation of electromagnetic waves. Antenna substrates are used to provide mechanical support for the antenna and to help shape and direct the electromagnetic field generated by the antenna. Antenna substrates have effects on antenna performance as well as providing mechanical support and shaping the electromagnetic field [13]. Ceramic and glass substrates are often chosen for their high dielectric constant, which allows them to support the propagation of electromagnetic waves with low loss. Plastic and metal substrates are often preferred for their low cost and ease of machining/ Overall, along with the radome application, in this study, a printed circuit board (PCB) patch antenna operating at f=8 GHz was investigated. Combined the radome application and patch antenna cases, the performance of quartz fiber is compared to other well-known, conventional alternative materials.

2. MATERIALS AND METHODS

2.1. PCB Patch Antenna Design

The patch antenna was designed by etching a metallic patch onto a dielectric substrate. The patch was then connected to a feed line, which supplies the RF energy to the antenna (Figure-1). The patch and feed line were designed to operate at a specific frequency or range of frequencies between 2 GHz to 20 GHz.

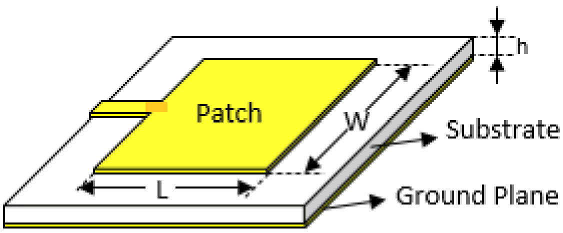


Figure 1. The schematic perspective view of the patch antenna

The dimensions of the patch antenna (W-width and L-length) used within the scope of the study were determined with the utilization of appropriate equations as shown below. In this study, dimensions of a patch antenna (W-width and L-length) can be calculated as follows;

$$W = \frac{c}{2f_0\sqrt{\frac{\varepsilon_R+1}{2}}} \text{ and } L = \frac{c}{2f_0\sqrt{\varepsilon_{eff}}} - 0,824h\left(\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0,258)\left(\frac{W}{h}+0.8\right)}\right)$$

Here, ε_R is the relative permittivity of the substrate used for the patch antenna, c is the speed of light, f_0 is the central frequency point, h is the thickness of the substrate.. In addition, ε_{eff} can be calculated as;

$$\varepsilon_{eff} = \frac{\varepsilon_R+1}{2} + \frac{\varepsilon_R-1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{h}{W}\right)}}\right]$$

In order to have operating frequency at f=8 GHz, W and L were optimized as 10 mm and 7.77 mm as shown below. In order to have better return loss, the feeding line was selected to have 1mm thickness as shown in the figure below (Figure 2).

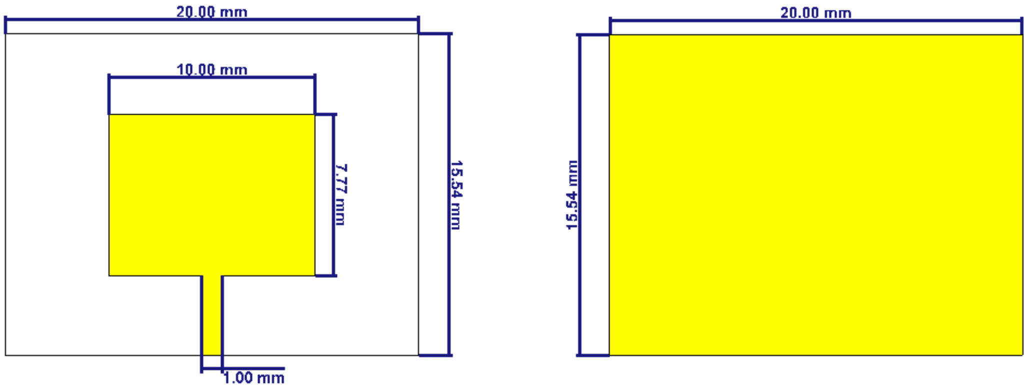


Figure 2. Dimensions of the designed PCB patch antenna (Left - Front side and Right – Back side)

2.2. Electromagnetic Characterization of Quartz Fiber and Glass

Quartz fiber and glass fiber specimens were manufactured in 30 cm x 30 cm dimensions in order to test on a free-space electromagnetic measurement setup, which involves the use of two linearly polarized high gain antennas and a vector network analyzer. A sample setup is shown below (Figure 3).

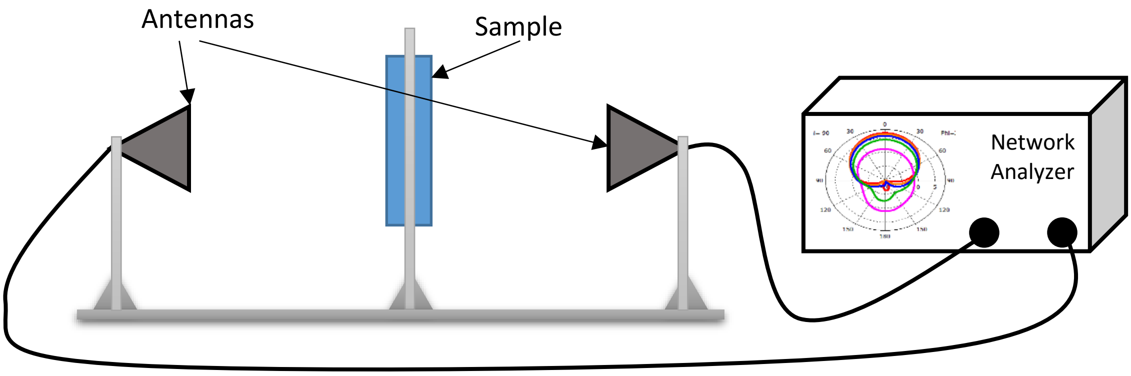


Figure 3. The schematic of the free space measurement setup

In this setup, the calibration was made using a metal plate and air for full Reflection and full Transmission. By using this method, the reflection and the transmission behavior of the sample under test were measured. These parameters are known as Scattering Parameters (S-parameters for short). There are a few methods to obtain electrical permittivity values from scattering parameters. One of the most commonly used one is Nicholson Ross Weir (NRW) method developed by Nicholson, Ross and Weir [17,18]. The obtained complex electrical permittivity (ε) values for the samples are given in the figure below for quartz fiber and glass.

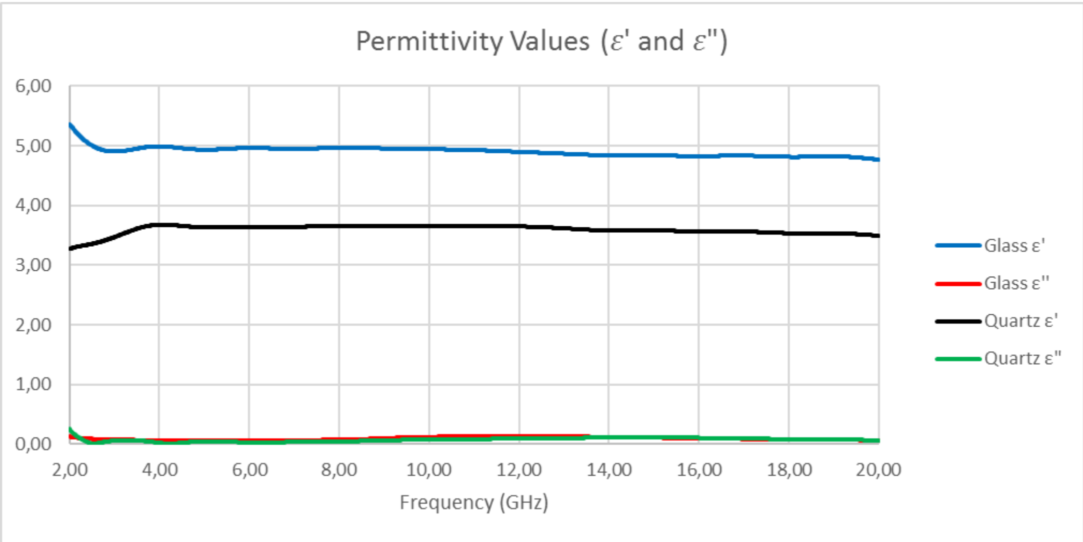


Figure 4. Electrical permittivities of glass and quartz fibers between 2 GHz to 20 GHz frequency range.

3. RESULTS AND DISCUSSION

The results will be given for two cases. The first case is about the use of Quartz Fiber as the substrate and the second case is about the use of Quartz Fiber as the radome of a patch antenna.

3.1. Quartz and Glass as the Substrate of the PCB Patch Antenna

A patch antenna is a type of radio frequency (RF) antenna that is commonly used in wireless communication systems. It is called a "patch" antenna because it consists of a flat or slightly curved rectangular patch of conductive material, which was chosen as copper in our case mounted on a dielectric substrate. The patch antenna is often mounted on a ground plane, which is also chosen as copper in our case. During the design phase, the substrate was selected as FR-4 to finalize the antenna design in order to set the operating frequency as f=8 GHz. The substrate material was then changed to Quartz and Glass fiber, respectively and the return loss graphs were obtained (Figure 5).

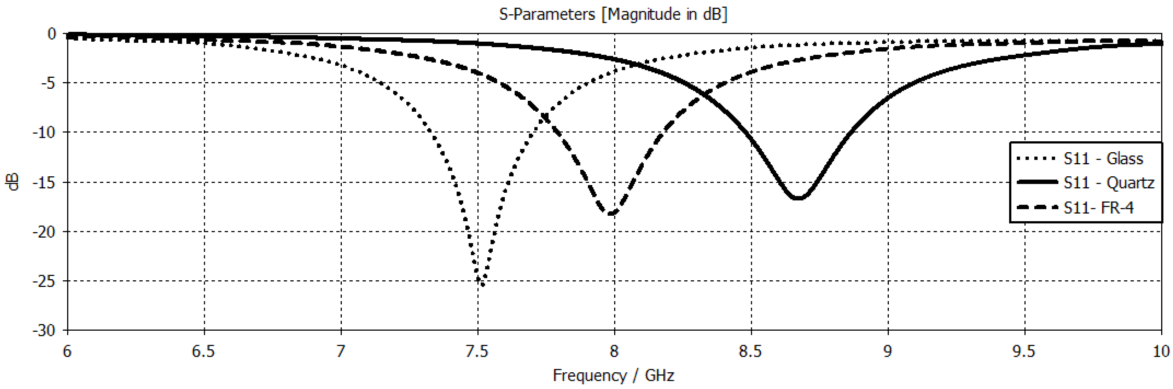


Figure 5. Return loss of the antenna with quartz, glass, and FR-4 substrates.

As observed in the return loss graphs (S11) of the designed antenna with different substrates, the antenna operating frequency shifts depending on the substrate type. Considering that the electrical permittivity value of FR-4 is about 4.3, glass fiber is about 5.2, and quartz fiber is about 3.7 we can easily say that the operating frequency shifts to higher frequencies as the permittivity value of the substrate decreases. The antenna operates at 8 GHz for FR-4 substrate, it shifts to a lower frequency (f=7.5 GHz) for Glass fiber substrate and shifts to a higher frequency (f=8.5 GHz). Therefore, the effect of the substrate must be considered while designing the antenna. Since these antennas may be used under different environmental conditions including different temperature values, the dielectric constant variation of quartz material was tested using the free space measurement setup with temperature controlled furnace. The measurement was performed starting from room temperature up to 175° (Figure 6). As seen in the figure, the electrical permittivity values of Quartz increase as the temperature increases. The temperature effect on the antenna performance in terms of the substrate used is examined by P. Kabacik and M. E. Bialkowski [19]. In their study, they classified the substrates under four different categories in terms of the dielectric values and their temperature dependence behaviors for microstrip patch antennas.

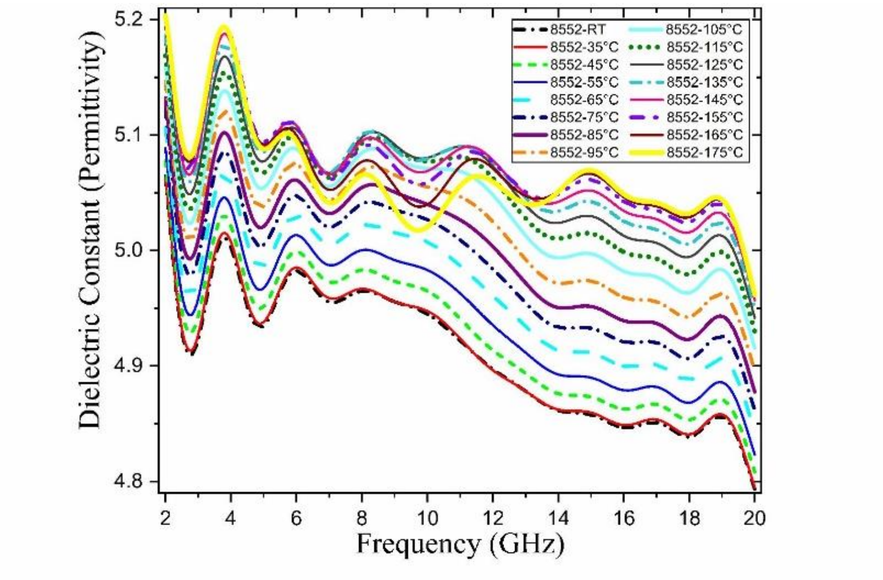


Figure 6. Dielectric constant of the quartz sample at different temperatures

In order to check the electromagnetic performance of an antenna, farfield radiation patterns should also be examined along with its return loss behavior. For this purpose, farfield radiation patterns have been obtained and the results are given in the figure below for three frequency points obtained in the return loss graphs (f=7.5 GHz, 8 GHz and 8.5 GHz) (Figure 7).

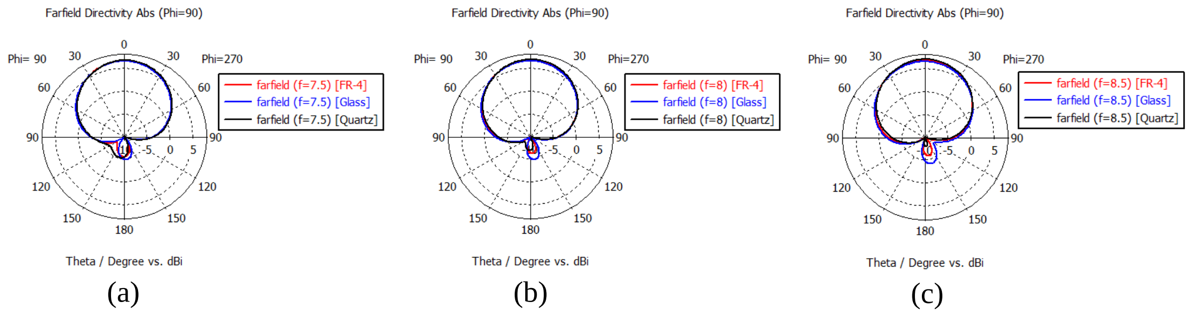


Figure 7. Farfield radiation pattern for quartz, glass, and FR-4 substrates at f=7.5, 8, 8.5 GHz.

Farfield radiation pattern plots are given in polar form showing the electromagnetic radiation behavior of the antenna in far-field region. From the radiation pattern plots, gain, half power beamwidth (HPBW), side lobes and back lobes of the antenna can be determined. As known, gain of an antenna is a quantity measuing the radiated electromagnetic energy in a particular direction which can be determined from the maximum radiation intensity of the main lobe in the radiation pattern. Half power beamwidth is the angle indicating the directional ability of the antenna. It is the angular width of the main lobe of the radiation pattern of the antenna showing the angle between two points where the radiation intensity is half of its maximum value. As shown in Figure 7, there is no significant difference between the ~~resutls~~ results with different substrates for all frequencies. However, there are slight changes in terms of back lobe magnitudes. In order to clarify the results, these parameters along with the front to back ratio and main lobe direction of the antenna were tabulated in Table 1. Here, the front to back ratio refers to the ratio between the main lobe and back lobe magnitudes. One can see from the table that the main lobe direction of the designed antenna does not change significantly with various substrates while HPBW changes up to 10° which can be used for applications requiring different HPBW. On the other hand, the antenna gain increases when quartz substrate was used compared to the other substrate materials.

Table 1. Performance parameters of the antenna for different substrates at the three frequencies.

Frequency (GHz)	Material	Gain (dB)	HPBW	Front to Back Ratio	Main Lobe Direction
7.5	FR-4	6.59	95.0°	-12.2	0.0°
	Glass	6.49	96.6°	-11.5	0.0°
	Quartz	6.67	93.5°	-12.0	2.0°
8.0	FR-4	6.72	94.4°	-13.0	0.0°
	Glass	6.55	97.1°	-11.5	1.0°
	Quartz	6.85	91.9°	-13.9	1.0°
8.5	FR-4	6.75	95.3°	-12.7	1.0°
	Glass	6.49	100.4°	-10.7	1.0°
	Quartz	6.98	91.1°	-15.0	0.0°

3.2. Quartz and Glass as the Radome of the PCB Patch Antenna

In this case, quartz and glass fiber were used as the radome of the designed PCB antenna. The radome shape is shown below (Figure 8). The thickness of the radome was selected as t=2 mm in the designed structure/ The control of the performance of the produced radome was carried out only with the far-field radiation model.

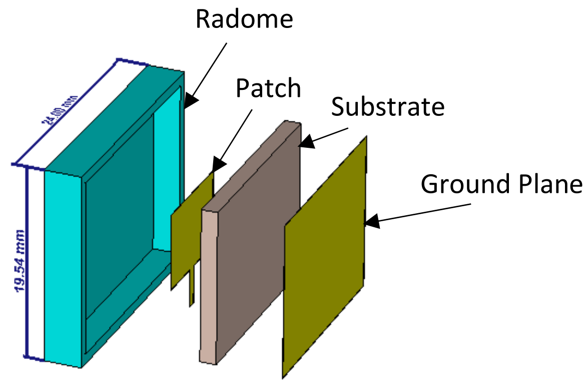
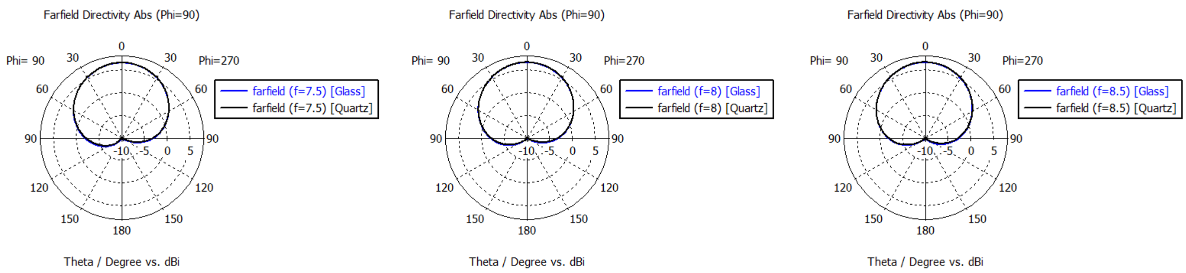


Figure 8. The schematic of the radome application on the designed PCB patch antenna.

The effect of the radome can be seen more clearly by examining the farfield radiation pattern of the designed antenna. In this case, the substrate was selected as FR-4 while changing the radome material between Quartz and Glass fiber. The farfield radiation patterns of the designed antenna for different radome materials were simulated for f=7.5 GHz, 8 GHz and 8.5 GHz, respectively. The results are given in the following figure (Figure 9). As seen in these figures the gain, main lobe direction and side lobe levels are almost the same for Quartz and Glass based radomes.



(a) (b) (c)

Figure 9. Farfield radiation pattern for quartz and glass substrates at f=7.5, 8, 8.5 GHz.

4. CONCLUSION

In conclusion, the uses of quartz fiber as an antenna radome and a dielectric substrate were investigated for a patch antenna designed to operate at f=8 GHz. . The well-known FR-4 substrate was also compared to quartz and glass-made substrates. In both cases, the antenna performance parameters including antenna gain, half-power beamwidht, main lobe direction and front-to-back ratio (the ratio between the main lobe and back lobe of the radiation pattern) were examined. In both cases, it was found that the use of quartz and glass fiber as the substrate and radome material shifts the operating frequency while it does not change the antenna radiation parameters significantly. The highest change was observed in the HPBW of the antenna up to 10° which can be used in application areas requiring sensitive coverage area. From this perspective, it was concluded that the electromagnetic performance of an antenna can be adjusted using these materials as radome and/or antenna substrate depending on the application type by also considering the environmental performances of the Quartz and Glass fiber reinforced materials.

CONFLICT OF INTEREST

The author stated that there are no conflicts of interest regarding the publication of this article.

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